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MODELLING SHEARING CHARACTERISTICS OF REINFORCED CONCRETE

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ABSTRACT. Numerical modeling represents the most versatile computational method for various engineering disciplines. Nowadays, numerical modelling is extensively used in civil and mining applications because of cost and risk problems associated with excessive field studies, particularly in ground control applications. In this study, the behaviour of shearing a fully grouted bolt with regard to assessing strata reinforcement (particularly in shearing) has been simulated. In addition, the effect of both different rock strength and different pre-tensioning levels with 3D numerical simulation are analysed. It was found that the strength of surrounding material contributed to the increased resistance of the installation and has reduced shear displacement; shear resistance increased with increasing bolt tensile load. Several laboratory tests were carried out in order to confirm the numerical results and the findings from the laboratory studies were found to be in agreement with modelling simulations.

Keywords: Shear bolts, Shear joint, Concrete strength, Initial load, grouted bolts, FEM.

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INTRODUCTION

Fully grouted rock bolts are widely used in both civil and mining engineering constructions as reinforcement elements. A fully grouted bolt in intersection with a joint has a great effect on the resistance to shear. Bjurstrom [8] was the first to report on the systematic research work on fully grouted rock bolts. According to Bjurstrom, the failure mode, strength and deformation stiffness of the sheared bolted joint were dependent on the bolt angle of installation across the joint. Dight [7] carried out a series of laboratory tests, to evaluate the shear resistance of bolted joints using various materials and found that the failure of the bolt was caused by the combination of axial and shear forces, that the normal stress acting on the joint surface had no influence on the shear resistance. Ferrero [2] found out that the overall strength of the reinforced joint was considered to be the combination of both the dowel effect and the incremental axial force increase due to the bar deformation. Further studies in the same field include those of, Yap and Rodger [5], Aydan [3], Swoboda and Marence [4].

Clearly, there remain a number of issues, which require further investigations, and this paper is concerned with the laboratory study and 3D numerical simulation study of the influence of bolt pretension on the shearing of joints in different strength concrete.

LABORATORY TESTS

Double jointed concrete blocks were cast for each double shearing test. Two different strength of concrete blocks were cast, 20 and 40 MPa strength to simulate two different strength rocks. Figure 1 shows an initial state of bolted joint with initial loads and other specifications. Fully grouted 22 mm diameter bolts were fixed in the concrete specimen using Miniva PB1 Mix and pour grout resin. Figure 2 shows the general set up of the assembled double shear box unit in a testing machine and sketch of a deformed bolt together with a post testing deformed bolt. The general method of testing required the application of a downward load to the centre block while the two end blocks remain stationary so as to shear the bolt as it resides within the blocks. Several bolt types were used for the study.

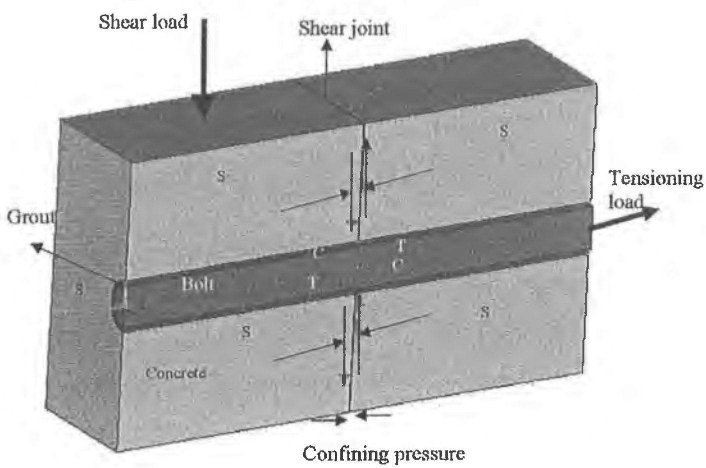
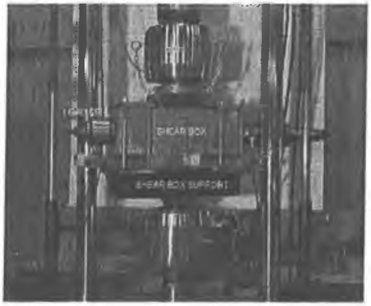


Figure 1 Initial state of bolted joint, one fourth of the model: C, T, S compression, tension and symmetric area respectively

Tests were made with axial confining loads of 0, 20, 50 and 80 KN. Shearing tests were conducted in 20 and 40 MPa strengths concrete blocks were to simulate soft and hard rock respectively. Figure 3 shows the typical shear load versus shear displacement in experimental tests.



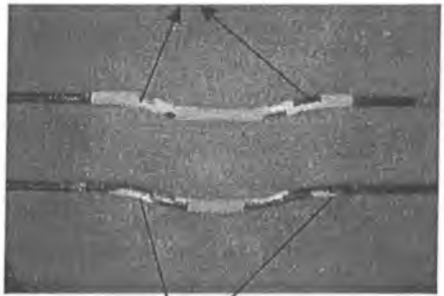


Figure 2 Photograph of tested sample in Instron testing machine and sketch of deformed bolt together with a post testing deformed bolt

LABORATORY RESULTS

The following points were noted from shear load and deflection graphs:

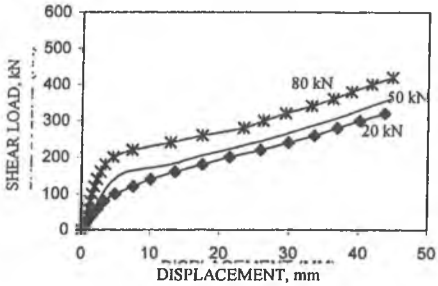
1 The strength of concrete has influenced the shear load level but not the trend. Shear load values for all bolts were generally less in 20 MPa concrete strength in comparison to the shear load values of bolts tested in 40 MPa concrete.

2 The strength of the concrete and the level of bolt pretension influenced both the elastic limits and stiffness of the bolt. As can be seen in Figure 3 the stiffness values in 40 MPa concrete were more consistent that the values that were in 20 MPa concrete, which are of diverse values. The stiffness level was defined as the gradient of the slope of the graphs section prior to the yield point.

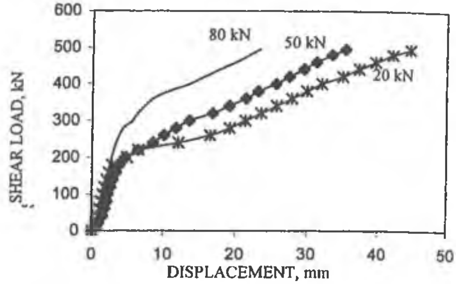
3 The hinge points distance decreased with increasing rock strength. The hinge point is defined as the point with the maximum moment and zero shear stress along the bolt axis.

3D NUMERICAL SIMULATION

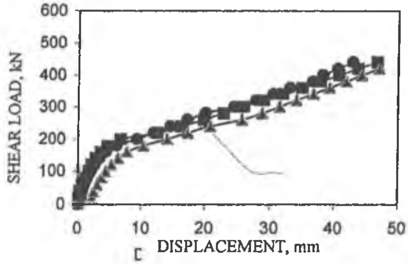
3D Numerical simulations were carried out in 20, 40 and 50 MPa concrete blocks to analyze the strains and stresses developed without pretension load and with the bolt pretension loads of 20, 50 and 80 kN. However, the figures are related to unpretensioned and 80 kN pretensioning. Parameters considered were, the three governing materials (steel, grout, and rock) with two interfaces (bolt - grout and grout - rocks). Using (ANSYS, Version 8), it was possible to simulate specifically the elasto-plastic materials and contact interfaces behaviors.



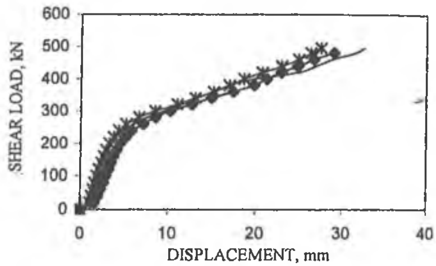
(a) Bolt Type 1 in 20 MPa concrete



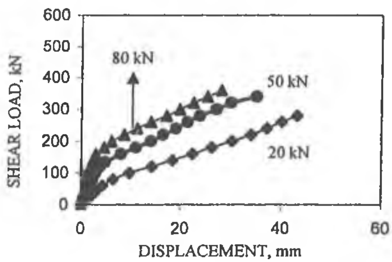
(b) Bolt Type 1 in 40 MPa concrete



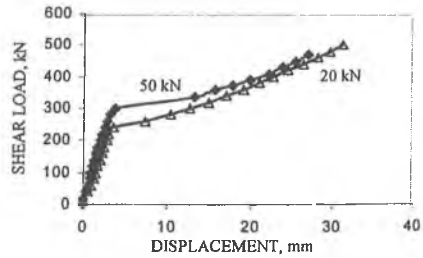
(c) Bolt Type 2 in 20 MPa concrete



(d) Bolt Type 2 in 40 MPa concrete



(e) Bolt Type 3 in 20 MPa concrete



(f) Bolt Type 3 in 40 MPa concrete

Figure 3 Shear load and shear displacement of bolts tested in both 20 and 40 MPa concrete strength and under different tensile loading conditions respectively

The model bolt core diameter (D_b) of 21.7 mm and the grouted cylinder (D_h) of 27 mm had the same dimensions as those used in the laboratory test. The results of both the numerical modeling and the experimental results, in different rock strengths and different bolt pretensions, are shown in Figures 4 to 6. It can be seen that the numerical simulations were found to be in close agreement with the experimental results. The 3D solid elements (Solid 65 and Solid 95) that have 8 nodes and 20 nodes were used for concrete, grout and steel respectively, with each node having three translation degrees of freedom, which tolerated irregular shapes without significant loss in accuracy. Simulation of several models in varying conditions (a range of bolt tensile load and concrete strength) was carried out under a vertical load and results were analysed for both linear and nonlinear regions of the load - deflection curve.

NUMERICAL RESULTS

Calibration of The Model

First, the numerical model was calibrated by the laboratory test afterwards the numerical simulation analyses were carried out in each of 20, 40 and 50 MPa strength concrete. The strains and stresses analysis were made with bolt pretension loads of 0, 20, 50, and 80 kN respectively.

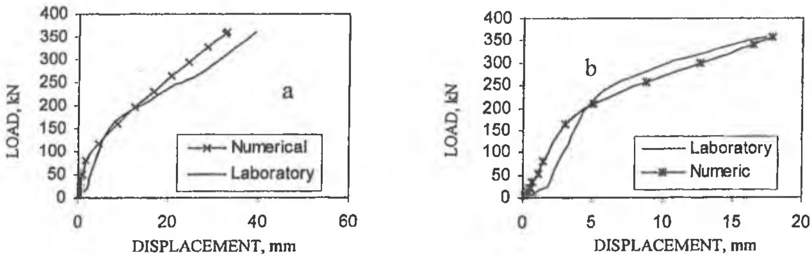


Figure 4 Load-deflection in 20 KN pretension bolt load with different concrete strengths, a: 20 MPa, b: 40 MPa

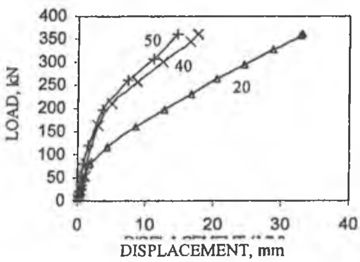


Figure 5 Load-deflection in 20 kN pretension bolt load in different concrete strength 20,40,50 (Numerical)

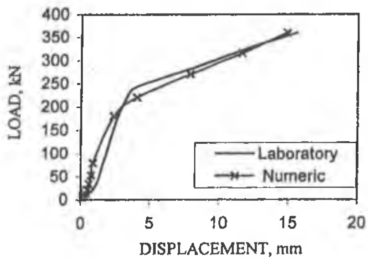


Figure 6 Load-deflection in 80 pretension bolt load in 40 MPa strength concrete

Steel Bolt

Steel bolt encapsulated nearly 3 mm thick resin in each of 20, 40, and 50 MPa strength concrete blocks were examined with respect to the changes in stresses and strains along the bolt. As figure 7 shows the stresses in the top part of the bolt and towards the perimeter are tensile, while it is compressive at the center. However, the stress conditions at the lower half section of the bolt are reverse. It was found that the tensile stress in the bolt was expanded and compression stress was reduced with increasing the pretension load. Figures 8 displays the rate of stress changes along the bolt axis.

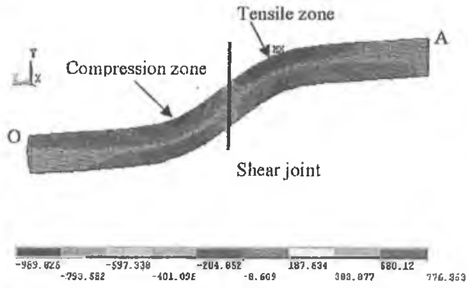


Figure 7 The stress contours along the bolt in 20 MPa strength concrete without pretensioning

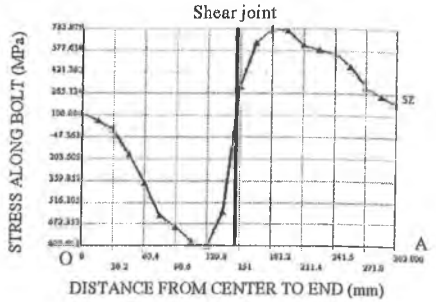


Figure 8 The stress contours along the bolt in 20 MPa strength concrete with 80 kN pretension bolt load

The rate of shear stress in the bolt in the vicinity of the sheared joint in 20 MPa strength concrete is shown in figure 9 and the shear stress contour is shown in figure 10. It is obviously evident that the pretension caused a reduction in shear stress. At the Post elastic yield point the shear stress was almost constant and was unaffected by the increase in both the shear and pretension loads. Shear stress diagrams for all concrete has the same trend. However, the value of shear stress was decreased with increasing the pretension load. This was in agreement with the maximum shear stress theory. The steel bolt yield situation began to occur after 33 percent of loading period. The yield limit of the steel, at the two hinges, is about 0.22 P and 0.32 P in 20 and 40 MPa strength concrete respectively (P is the maximum tensile strength of the bolt). Further increase in the shear force has no apparent influence on the stresses in the hinges. The distance between hinge points is reduced by increasing the strength of material.

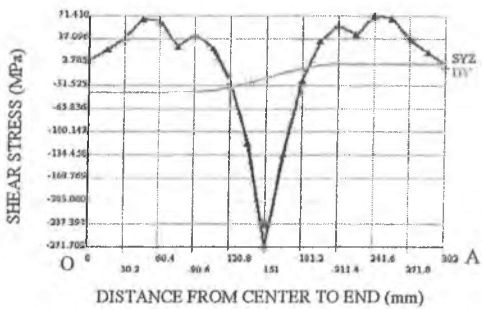


Figure 9 Shear stress trend in 20 MPa strength concrete without pretensioning

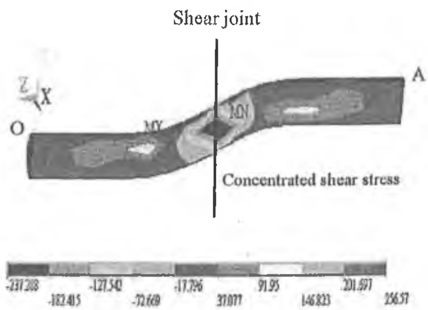


Figure 10 Shear stress contour in 20 MPa strength concrete with 80 kN pretensioning

Figures 11 and 12 show the rate of strain changes and strain contours along the length of the bolt respectively. Softer concrete has experienced higher strain. Induced strain is increased with increasing the shear load. Figures 13 shows the rate of Von Misses strain along the bolt axis. With increasing the pretension load in post failure behaviour there is no significant changes in strains along the bolt. However, the area of tensile strain is expanded and compression strain is reduced. From the comparison of the plastic strain in concrete 20 and 40 MPa it is recognized that strains in weaker media are higher than harder media in both tension and compression zones. This situation is observed in all of different pretensioning. Figure 14 shows the relationship between bolt pretension load and bolt resistance factor (F) defined as the ratio of shear force and bolt tensile yield strength. Resistance factor increases with an increasing tensile load. Increasing the strength of surrounding materials and higher pretensioning finds resistance factor increases. Thus shear resistance is reached at a higher than maximum tensile strength than the bolt.

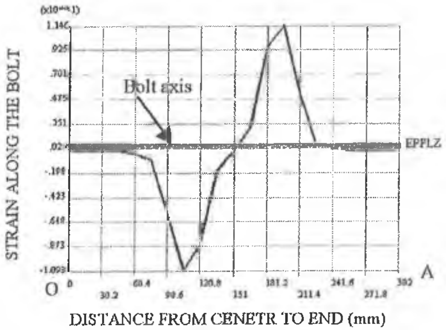


Figure 11 Strain contours along the bolt in 20 MPa concrete strength with 20 kN pretensioning

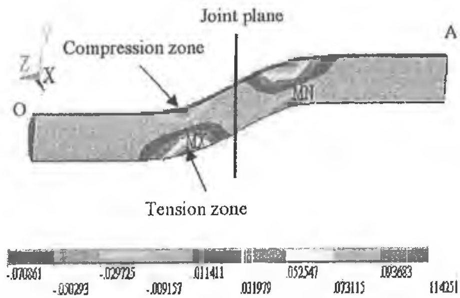


Figure 12 Strain contours along the bolt in 20 MPa concrete strength with 80 kN pretensioning

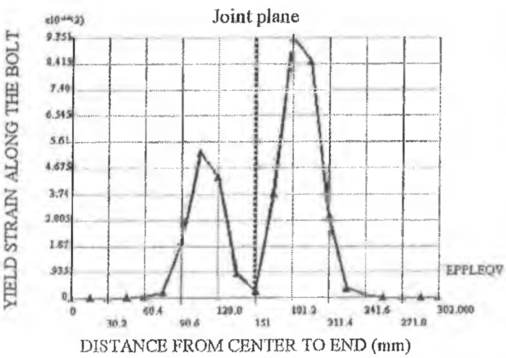


Figure 13 Von Mises strain trend along the bolt axis in 20 MPa strength concrete with 80kN pretensioning

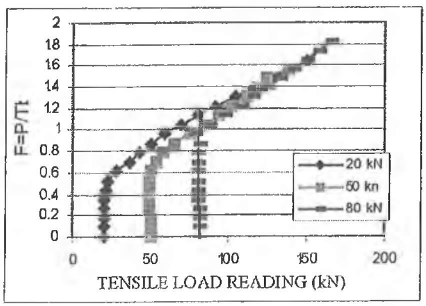


Figure 14 Effect of pretension bolt load on load factor. On the vertical axis the ratio of shear force on the bar tensile yield strength

Examination of the plastic strain behavior in both 20 and 40 MPa strength concrete lead to the following deductions:

- The strains in weaker media were higher than the strong concrete in both the tension and compression zones at all bolt pretension load.
- The value of strain in the tension zones was higher than the compression zones. This is clearly evident in the tension and compression zones around the bolt as shown in Figure 12.
- There are two hinge points around the shear plane, and the distance of each hinge point from shear plane is approximately equivalent to 2.4 D_b, or 53 mm (D_b is the bolt diameter). This distance is simulated in a 20 MPa concrete and with bolt pretension load of 20 kN. However, the laboratory test hinge spacing distance was around 44 mm ($2D_b$). At both hinges, the numerical simulation produced the elastic yield limit at about 0.22P and 0.32P in 20 and 40 MPa respectively (P is the maximum tensile strength).
- There was no apparent influence on the stresses at the hinges, with further increases of the shear force. However, there was a reduction in hinge distance with increased concrete strength.

Concrete

Often Concrete is used in lieu of rock for various geomechanics studies, as working with rocks is laborious and costly. Usually rock samples are difficult to prepare as regular samples, so different strengths of concrete (20, 40 and 50 MPa) were prepared with similar rock strength. The behavior of concrete under the shear load was analysed. Stress contours in concrete along the bolt length are shown in figure 15. The high level of stress produced in the concrete caused fractures and failures in the vicinity of shear joint regions. However, the zone of high stress concentration in weaker concrete is significantly broader; 90 mm from the shear plane, in comparison to 60 mm obtained from high strength concrete. Figure 16 shows the rate of stress changes along the bolt produced in 20 MPa strength concrete.

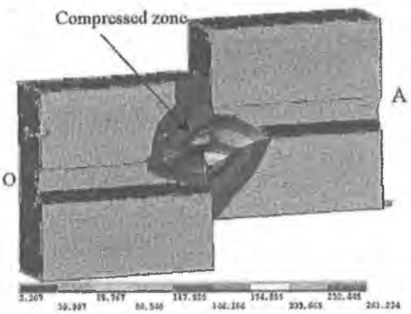


Figure 15 Induced stress in 20 MPa strength concrete without pretensioning

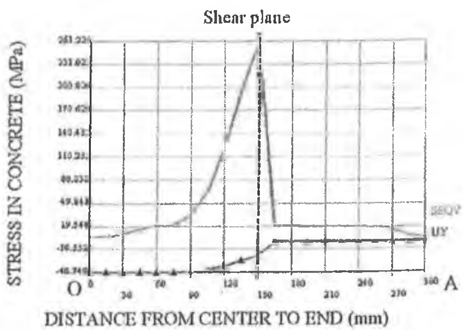


Figure 16 Yield stress and displacement trend in 20 MPa strength concrete without pretensioning

The values of compressive and tensile strains are decreased with increasing pretension effects. Figure 17 displays the deformational behavior of both the concrete medium and bolt. The plastic deformational of concrete occurs at 10 % maximum shear loading application, while the deformation of the bolt past yield point occurs at 33% of loading.

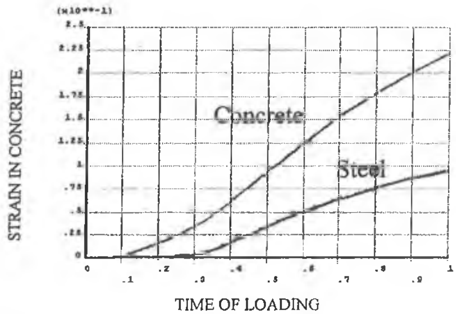


Figure 17 Strain induced in concrete and bolt in 20 MPa concrete strength and 80 kN pretension load

Grout

Figures 18 and 19 show the induced strain trend and contours along the grout layer in an installation consisting of 21.7 mm core diameter bolt and 27 mm diameter hole in 20 MPa strength concrete with different pretensioning. As figures show the value of the compression strain is reduced with increasing pretensioning. The value of strains in grout layers was 10 times greater than the linear region at critical zones, thus grout in those areas had broken off the sides that were in tension (Figure 2). Figures show the value of strain in the vicinity of shear plane through the grout is high and grout in that region fails.

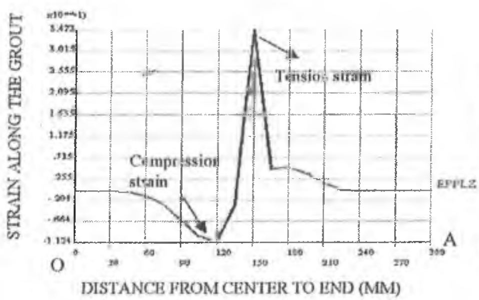


Figure 18 Plastic strain induced along the grout thickness in 20 MPa strength concrete without pretension load

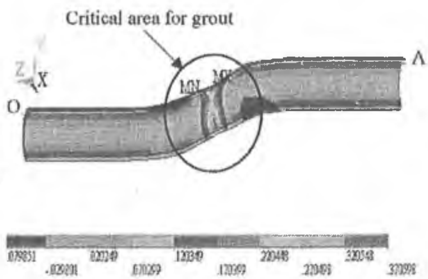


Figure 19 plastic strain contours along the grout layer in 20 MPa strength concrete with 80 kN pretension load

CONCLUSIONS

The study on the interaction between bolt, grout and rock during the shearing process was carried out both in the laboratory and by the numerical modelling simulation. The main conclusions drawn from both the experimental and numerical modelling are as follows.

- The composite bolt/concrete deflection at a given vertical load was higher in weaker medium.
- Pretensioning has reduced axial deformation of the bolt. Pretensioning of the bolt caused a reduction in deflection with increasing surface shear resistance.
- Tensile and compressive stresses zones along the bolt are located on each side of the shear plane. The nature of stress concentration is dependent of the deflection direction of the sliding blocks relative to each other.
- Different initial tension levels do not appear to influence shear deflection prior to elastic yield points, the influence of bolt pretensioning becomes evident post elastic yield point of the bolt.
- For small-applied loads (before yield point), pre-tensioned, does not influence much on the magnitude of the shear displacement and resistance of the system. That is evident for both experimental and FE results
- Of the three bolt types tested experimentally, the shear load of the bolt, in general, increased with increasing bolt tension. This behaviour was obvious for bolt type T1. There was almost no change in shear load in bolt type T2 and ironically there was a decline in shear load in bolt type 3.

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